TRACKING AND DATA RELAY SATELLITE (TDRS-3) RANGE BIASES AND MOMENTUM UNLOAD MODELING FOR TERRA (EOS-AM1)*

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ABSTRACT

The Flight Dynamics Facility (FDF) reports its performance in meeting Tracking and Data Relay Satellite (TDRS) predicted ephemeris accuracy requirements with TDRS-3. The Terra (Earth Observing System AM-1) satellite has 3σ TDRS requirements of 75 meters for total position accuracy predicted over 1 day onboard. The study sample includes selected cases over 21 months after Guam Remote Ground Terminal (GRGT) support started in June 1998. For daily solutions with a 1.5-day prediction span, predicted results of the study were below the Terra requirement by at least 12 meters.

Refined range bias estimation and modeled momentum unloads are needed to meet Terra's requirements for TDRS-3. Maintained at 275 degrees west longitude over the zone of exclusion, TDRS-3 is analyzed separately from other TDRSs because of its unique tracking data. Only the Bilateration Ranging Transponder (BRT) at Alice Springs (ALS), Australia, and the Telemetry, Tracking and Command (TT&C) system at Guam are used for routine operational tracking data for TDRS-3. Simultaneous batch orbit solutions with three TDRSs and either the Compton Gamma Ray Observatory (GRO) or Terra were done with the Goddard Trajectory Determination System (GTDS) to periodically refine the TT&C and BRT System (BRTS) range biases. As new biases were determined, significant changes were made in estimating the absolute position. FDF achieved similar results using a sequential filter with all operational TDRSs and four user satellites. Definitive accuracy (3σ) is expected to be below 50 meters.

The White Sands Complex (WSC) performs momentum unloads to maintain three-axis stabilized attitude of TDRSs. The relationship between velocity changes (delta-V) and reaction wheel speed changes was empirically determined for roll/yaw unloads. A theoretical relationship was verified and used for pitch unloads. Modeling both pitch and roll/yaw momentum unloads is necessary to meet the 75-meter requirement. Moving the orbit solution epoch an hour before a momentum unload can improve delta-V optimization and prediction accuracy over 1.5 days.

INTRODUCTION

In this paper, the Flight Dynamics Facility (FDF) at the Goddard Space Flight Center reports performance in meeting Tracking and Data Relay Satellite (TDRS) predicted ephemeris accuracy requirements with TDRS-3 for the Terra (Earth Observing System AM-1) satellite. The 3σ requirements are 75 meters total positional accuracy and 5.5 millimeters per second total velocity accuracy predicted over 1 day onboard (Reference 1).

TDRS-3 is maintained at 275 degrees west longitude over the TDRS System (TDRSS) zone of exclusion (excl.). Figure 1 is a map of TDRS longitudes and ground tracking and relay sites. TDRS-3 is analyzed separately from other TDRSs because of its unique tracking data. Since June 1998, only the Bilateration Ranging Transponder (BRT) at Alice Springs (ALS), Australia, and the Telemetry, Tracking and Command (TT&C) system at Guam are routinely used for operational tracking data for TDRS-3. While other operational TDRSs track BRTs at two sites, only one BRT and the Guam Remote Ground Terminal (GRGT, referred to here as Guam) are used for TDRS-3 tracking data. This paper describes extra analysis done to assess TDRS-3 range biases for both tracking systems. Although the desired consistencies were achieved for TDRS-3 with the initial range biases, significant changes in estimating the absolute position were made as new biases were determined.

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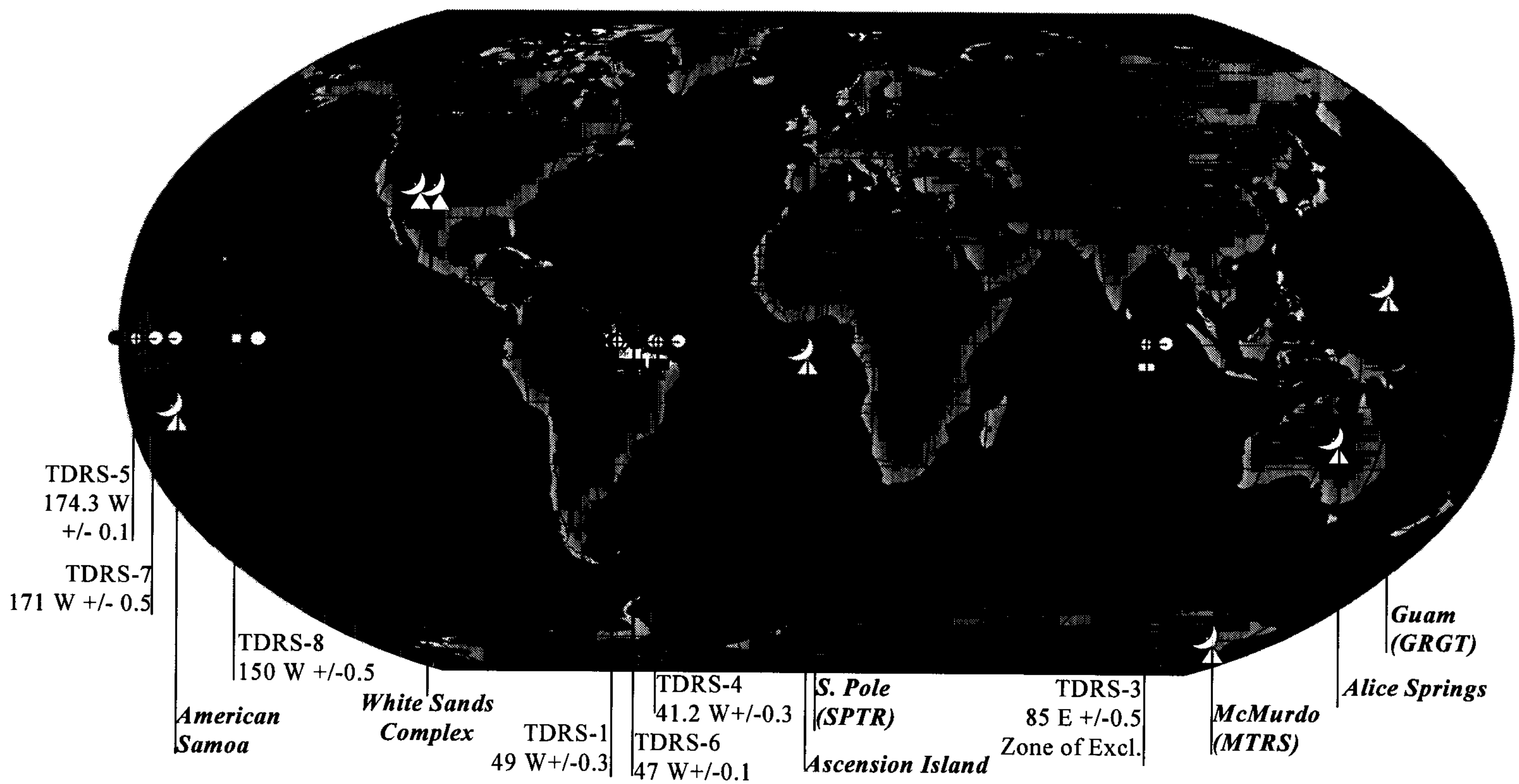

Figure 1. Map of TDRS Longitudes and Ground Tracking and Relay Sites in July 2000

In December 1999, Reference 2 reported progress toward meeting these requirements by modeling both pitch and roll/yaw momentum unloads for all other operational TDRSs. This TDRS-3 study includes results of modeling both pitch and roll/yaw momentum unloads.

The first section presents background information on modeling, requirements, accuracy, and momentum unloads. Then methods and results of orbit determination, including range bias estimation, are discussed, followed by methods and results of momentum unload modeling. Finally, a summary and recommendations are given.

1. BACKGROUND

TDRS-3 Characteristics and Modeling

Table 1 gives the current TDRS-3 location and function status, stationkeeping longitude and box size, and the inclination on April 29, 1998. The current inclination is listed at http://mmfd.gsfc.nasa.gov.

Table 1. TDRS-3 Information

TDRS Status	**Position**		**Inclination**
	Longitude (degrees)	**Box** (+/-degrees)	on April 29, 1998 (degrees)
Zone of Exclusion	275 West (85 East)	0.5	3.8

The standard modeling used for TDRS-3 during this study, which includes modeling both pitch and roll/yaw momentum unloads, is listed in Table 2. The **boldface** parts are different from what was used for other TDRSs in Reference 2, which describes the first known delta-V calibration of TDRS roll/yaw unloads. As recommended in Reference 2, operational TDRS solutions are being updated on a daily schedule.

Relationship between Position and Velocity Requirements

The first momentum unload study by FDF considered only pitch unloads and showed that, when the positional accuracy requirement (75 meters, 3σ) was met, the velocity accuracy requirement (5.5 millimeters per second, 3σ) was also met (Reference 4). Therefore, this study only addresses FDF's ability to meet the positional accuracy requirement.

Definitive Accuracy

Definitive solutions are used as a baseline from which to assess the predicted errors of ephemerides. Therefore, the definitive accuracy of a solution must be estimated before the measured predicted accuracy can be interpreted as an absolute accuracy.

For the current study, the average definitive consistency was computed from the maximum position differences between overlapping definitive ephemerides over 1/2 orbit (12 hours), at the typical end of overlapping tracking data. Results were adjusted to remove the effect of updates to the difference of Universal Time based on earth's rotation (UT1) and Coordinated Universal Time (UTC). Because of the uncertainty of the TDRS-3 range biases, the definitive consistency may be small (10 meters) while the definitive accuracy could have a large (100-meter) constant offset. The definitive accuracy is also addressed in the range bias estimation part of Section 2.

Table 2. TDRS-3 Standard Modeling Parameters

Parameter	Value
Data arc length	**1 day + 18 hours (42 hours)**
Geopotential model	75x75 JGM-2 truncated to 8x8, with constant J_2 term over time
Noncentral bodies	Sun and Moon
Coordinate integration reference system	Mean of J2000.0
Coordinate integration system	Keplerian
Integration type (step size)	Cowell fixed step (300 seconds)
Atmospheric density model	Not Applicable
Atmospheric drag coefficient	Not Applicable
Tropospheric refraction model	Saastamoinen/Niell/Radomski model for TDRSS refractive delays (Reference 3)
Solar reflectivity coefficient (C_R) (estimated)	between 1.35 and 1.47
Satellite geometry model	Sphere with cross-sectional area of 40 meters^2
Timing delays applied through GTDS	–54.7 nanoseconds for American Samoa BRTS
Estimated parameters	State vector, C_R, composite range bias
Tracking data types	BRTS range **and TT&C range**
Input range biases	**see section 2**
Polar Motion	On
Tides	Off
Antenna offsets	GTDS 99.01 defaults
Covariance constraints	10^{-12} degree^2 for both inclination and right ascension of ascending node
Shadow modeling	Conical umbra/penumbra

Studies before momentum unload modeling began indicated that definitive dual BRTS-based solutions had 3σ accuracies of approximately 100 meters (References 5 and 6). For TDRS-3, an error analysis estimated an achievable accuracy of less than 54 meters (3σ) with K-band TT&C and BRT System (BRTS) data from ALS (Reference 7). If, however, the TT&C bias was uncalibrated and had an uncertainty of 60 meters, position errors would vary from 78 to 444 meters. The ionosphere was indicated as the next major error source after range biases. The estimation of the range biases is discussed in section 2 below.

Predicted Accuracy

Predicted accuracy is a measure of how well a solution holds up with propagation over a length of time. It is assessed by comparing a predicted ephemeris to a definitive ephemeris. Predicted accuracies of TDRS solutions were assessed for 1.5-day spans and 2.5-day spans. These two spans are relevant for either the daily solution schedule, or three-sevenths (Tuesday, Thursday, and Saturday) of a Monday-Wednesday-Friday (M-W-F) solution schedule with no solutions done on Tuesday, Thursday, Saturday, and Sunday, when only ephemerides would be updated (Reference 4). The daily solution schedule has been in effect since December 6, 1999, which was 12 days before the launch of Terra.

It is expected that the measured predicted accuracy, which is computed *relative* to the definitive ephemerides, will still be applicable, even though the *absolute* definitive accuracy may undergo a significant correction by changing the range biases.

Momentum Unloads

The White Sands Complex (WSC) performs momentum unloads so momentum wheels will maintain an appropriate three-axis stabilized attitude of a TDRS. In preparation for Terra support, WSC began sending the times and both predicted and definitive reaction wheel speed (RWSP) changes of momentum unloads to FDF. These unloads are either pitch or roll/yaw. In Figure 2, +P and –P indicate pitch thrusters; while +R and –R indicate roll thrusters. Both pitch and roll thrusters have a significant thrusting in the –Z direction, while the yaw thrusters should all be entirely in the XY-plane. Z1 and Z3 form a yaw thruster pair; Z2 and Z4 form another yaw thruster pair. Each triangle represents a pair of thrusters. +X points towards the velocity vector, +Y points near the south celestial pole, and +Z points towards the Earth.

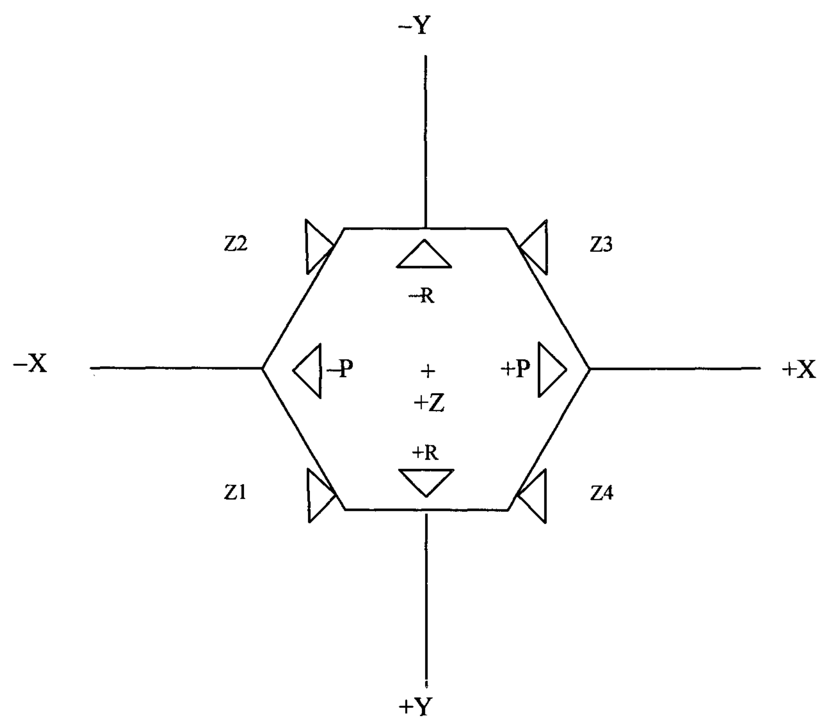

Figure 2: TDRS Momentum Unload Thrusters

From pitch thruster pointing, a linear relation of a pitch unload RWSP change and the delta-V in the along-track direction was derived[1]. Because of the good performance of this theoretical model, no adjustments are made operationally for other TDRSs (See Reference 4).

[1] Computer Sciences Corporation, internal report on momentum unload modeling, T. Lee, February 1998.

By being performed with paired thrusters (Z1/Z3 or Z2/Z4), roll/yaw unloads are intended to have no effect on TDRS orbits. However, misalignments or unequal thruster performance could induce orbital effects. Gas bubbles in the roll/yaw thruster fuel lines may affect thruster performance (Reference 8). These effects vary between TDRSs and between thruster pairs on the same TDRS (See Reference 4). Therefore, an empirical calibration for both roll/yaw thruster pairs is needed for each TDRS.

TDRS-3 has the least roll/yaw unloads with a 12-day average; TDRS-4 has the most with a 3-day average (See Table 3).

Table 3. Days Between TDRS Roll/Yaw Momentum Unloads
8/22/97 – 12/22/98

	TDRS-1 (days)[1]	TDRS-3 (days)[2]	TDRS-4 (days)	TDRS-5 (days)	TDRS-7 (days)
Average	9.2	**11.8**	2.9	4.7	8.3
Standard Deviation	9.6	**7.6**	0.8	2.9	8.1
Maximum	41	**28**	5	18	50
Minimum	0	**1**	0	0	1
Sample Size (counts)	48	**20**	168	103	50

1. Fourteen of the TDRS-1 roll/yaw unloads occurred on June 13 and 14, 1998, after an emergency time out (ETO).
2. The TDRS-3 sample above includes about 7 months: mainly 3 months after Guam support started in June 1998 and from December 8, 1999 until April 7, 2000.

2. ORBIT DETERMINATION METHODS AND RESULTS

First, the study period and selected samples are described, along with the software that was used. Then the estimation of range biases is explained and results are presented.

Study Period and Sample Selection

Since June 1998, TDRS-3 has been supported from Guam. The study period began after this time and extended until January 18, 2000. Several days were assessed around selected momentum unloads, including three cases that did not model roll/yaw unloads and failed to meet requirements in December 1999. This was when operational TDRS solutions reverted to a daily schedule just before the launch of Terra on December 18. Results of eighty-three cases are reported, including eight pitch unloads and twelve roll/yaw unloads. TDRS-3 averages a pitch unload every 20 days and a roll/yaw unload every 12 days. This would make up to five pitch unloads and eight roll/yaw unloads in a typical 83-day span. This sample has over fifty percent more unloads than the average. Because the worst accuracies occur when modeling momentum unloads, our results may therefore be worse than a more representative sample.

Software

The Goddard Trajectory Determination System (GTDS) 99.01 versions up to Delta-2 were used to perform orbit determination and ephemeris generation.

Range Bias Estimation

Both TT&C and BRTS biases were estimated (solved for) in orbit solutions. Two challenges were encountered in this process: the biases were always strongly correlated, and an occasional sudden change in one bias often degraded the other bias (See Reference 9). The latter challenge is discussed first, followed by correlations and the analysis done with other tracking data, including simultaneous solutions with satellites tracked by TDRS-3.

During the summer of 1998, BRTS range biases twice changed by 30 meters, once positive and once negative. The TDRS-3 MA and SA services were scheduled on every other day, and their biases changed a day apart of each other. This challenge was addressed by using an input standard deviation (SD) of 30 meters for the BRTS bias, and an input SD of 5 meters for the TT&C bias. These values helped to favor the TT&C data more than BRTS.

For 2 years, no other BRTS bias 30-meter changes occurred, but TT&C biases changed by integrals of 300 meters occasionally. The major range tone used for TT&C data for TDRSs is a sine wave at 500 kHz modulated on the uplink carrier. The maximum possible phase difference corresponds to a delay of 2 μsec, which is a 1-way range ambiguity of approximately 300 meters[2]. To reduce vulnerability to TT&C range ambiguity, the input TDRS-3 SDs were swapped to 5 meters for BRTS and 30 meters for TT&C on August 10, 1999. Sometimes the TDRS-3 TT&C bias change is immediately corrected by WSC, and sometimes it persists for a day.

On October 5, 2000, the BRTS SA range bias appeared to change by –10 meters. Three days later, the MA range bias followed, with the net result being a joint bias averaging 0 instead of 6 meters. Therefore, the input TDRS-3 SDs were switched back to again favor TT&C data over BRTS. Six days later on October 14, the MA bias seemed to jump back up. On October 25, 2000, a request went into effect to only schedule only one service type (either MA or SA) for TDRS-3 BRTS events. This should make bias modeling with GTDS simpler until an enhancement separates MA and SA biases.

An investigation was attempted to uncover the cause of the BRTS bias changes. WSC and Guam personnel were contacted, and the WSC Daily Operations Summaries were reviewed from October 3 through 8. Guam had power outages on October 5, 8 hours after the SA bias dropped, and on October 8, 4 hours before the MA bias drop was seen. No explanation for the bias changes was found.

The TT&C and BRTS range biases were always highly correlated. Both sites are east of TDRS-3 and are at similar latitudes in opposite hemispheres (See Figure 1).

Initial attempts to assess the TT&C range bias used the GRO Remote Terminal System (GRTS) range and Doppler data with BRTS and TT&C data. When GRTS began in December 1993, its range data was assessed relative to the collocated Deep Space Network site (DSS-46) in Canberra, Australia. Using the GRTS data as a reference point in June 1998, the initial coarse bias estimates at Guam were –25 meters for TT&C and +20 meters for BRTS. The input or "a priori" bias strongly influences the estimated or solve-for bias in TDRS-3 TT&C and BRTS-based solutions, because of the limited viewing geometry and the small dynamics of a geosynchronous satellite relative to a ground site.

Later bias determination used simultaneous solutions with GRO, TDRS-3, -4, and -5, or with Terra, TDRS-3, -7, and either -4 or -6. Other than the International Space Station, which has frequent maneuvers, GRO and Terra were the two users for which we have the most TDRS-3 tracking data. The simultaneous solutions used both range and Doppler data and had great variety in both viewing geometry and dynamics.

Table 4 shows consistent bias results from GRO simultaneous solutions between March and May 1999. The analytic calibration of biases (ACB) method (See Reference 10) provides a technique of range calibration for each of several components using six solutions to achieve the best TDRS-user solution. The timing delay in Table 2 for

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[2] Stephen D. Hendry, "TDRS Direct Tone Ranging", Flight Dynamics Facility internal document, April 3, 2001

American Samoa BRTS filled the primary need of ACB solution 1 for other TDRSs. Because a composite BRTS-TDRS-ground terminal bias is used operationally, ACB solution 2 is deemed sufficient to obtain the range biases for the purposes of this study. The solutions' time spans are listed, along with the TDRS-3 TT&C and BRTS (ALS) range biases measured from Guam. The average biases and SDs are shown. The SD column is from the GTDS' estimation of the range bias, while the Bias SD column is computed from the listed biases. The weighted average (wt. avg.) is obtained by weighting a bias by the inverse of its variance (square of SD), and dividing the sum of the weighted biases by the sum of the inverse variances (Reference 11).

Table 4. TDRS-3 Bias Summary from Spring 1999 GRO-Simultaneous Solutions

	Bias	SD	Bias	SD	Bias	SD	**Bias**	**Bias**	**Bias**
Span (m/dd.hh)	3/16.06-3/19.15		5/10.09-5/13.17		4/5.0 - 4/8.0		**Avg.**	**SD**	**Wt. Avg.**
TT&C	−43.5	0.7	−42.2	0.4	−42.5	0.4	**−42.7**	0.7	**−42.5**
ALS	−23.1	1.2	−18.6	0.7	−16.0	0.7	**−19.2**	3.6	**−18.1**

Input biases of −43 and either −18 or −19 meters were used on all data in this study before August 24, 1999. When the one-way, one-leg TT&C input bias was changed by 18 meters in May 1999, the TDRS-3 position changed by 135 meters in the along-track direction. This change in position is a factor of 7.5 greater than the range change.. The range measurement of a TDRS is primarily in the radial direction.

The positions of the other TDRSs in the simultaneous solutions usually agreed with the operational BRTS-based positions within 30 meters.

GRO simultaneous solutions in August and December 1999 had significantly different biases for TDRS-3. The TT&C and ALS biases determined in August were −13 and −3 meters, respectively. The TT&C and ALS biases determined in December were 3.3 and 24.5 meters, respectively.

The simultaneous solutions with GRO in January and February 2000 gave results that were even more varied. Simultaneous solutions with the recently launched Terra gave results more consistent with the August GRO results. The weighted average biases of the 2000 GRO solutions agree well with the Terra solutions. Table 5 lists the biases, SD, and weighted average bias using GRO in early 2000, which includes times of high atmospheric density fluctuations after increased solar-terrestrial activity. (GRO was deorbited in June 2000.) Table 6 lists the same parameters using Terra in early 2000. Because the weighted average biases agreed so well between the GRO and the Terra simultaneous solutions, new input biases of −7 and +6 meters for TT&C and ALS, respectively, were used starting on February 11, 2000. Most of the Terra data in the first 7 hours of the span from February 5 to 7 was rejected because of Terra thrusting. Thereafter the Terra data was very stable, and the TDRS-7 simultaneous solution was within 18 meters of the operational solution on February 9, 2000.

Table 5. TDRS-3 Bias Summary from Early 2000 GRO Simultaneous Solutions

	Bias	SD	Bias	SD	Bias	SD	Bias	SD	**Bias**	**Bias**	**Bias**
Span (m/dd.hhmm)	1/1.12-1/4.0430		1/6.16-1/8.0840		1/15.08-1/17.2350		2/5.0-2/8.0		**Avg.**	**SD**	**Wt. Avg.**
TT&C	−3.2	0.6	65.0	2.0	−20.0	0.4	7.5	0.5	**12.3**	36.9	**−7.5**
ALS	10.0	1.0	135.0	3.0	−19.5	0.8	31.2	0.9	**39.2**	67.2	**7.9**

Table 6. TDRS-3 Bias Summary from Early 2000 Terra Simultaneous Solutions

	Bias	SD	Bias	SD	**Bias**	**Bias**	**Bias**
Span (m/dd.hhmm)	1/3.06-1/5.0745		2/5.0-2/7.12		**Avg.**	**SD**	**Wt. Avg.**
TT&C	−6.8	1.4	−6.5	0.2	**−6.7**	0.2	**−6.5**
ALS	3.9	2.4	5.6	0.3	**4.8**	1.2	**5.6**

With the change of biases in February 2000, the GTDS estimate of the TDRS-3 position changed by 71 meters westward. Combining the March, April, and May 2000 Terra solutions with the prior Terra solutions precisely confirmed these values; these Terra solution TT&C biases were all within 3 meters of each other.

Figure 3 displays the input BRTS and TT&C biases used for TDRS-3 since Guam support began. The current input BRTS bias last changed from 6 to 0 meters on October 13, 2000, after MA and SA biases changed. The early evolution of the input biases over time may be more indicative of solution variations than of bias changes.

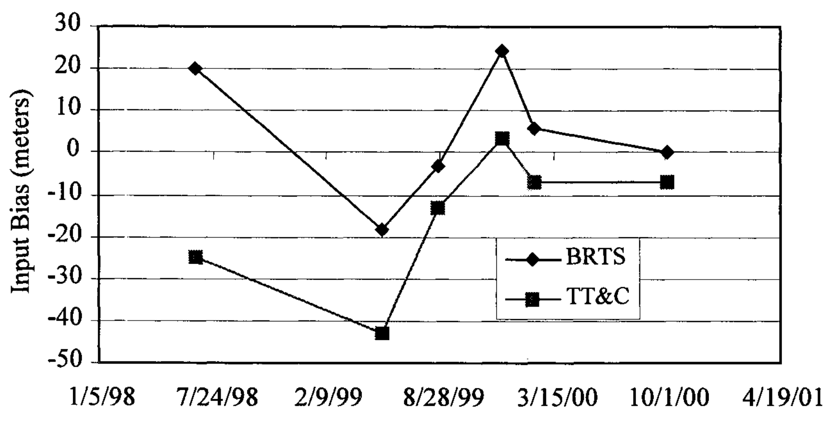

Figure 3. TDRS-3 Input Biases

Occasionally DSS-46 is used to track TDRS-3, providing an independent tracker with typically a small bias. On August 14 and 15, 2000, the mean DSS-46 range residual relative to an operational solution with TT&C and BRTS data was −8.2 meters. The default measurement SDs are 20 meters for DSS Universal Tracking Data Format (UTDF) range data and 10 meters for both BRTS and TT&C. Before April 2001, this and other DSS-46 range passes have confirmed the operational TT&C and BRTS biases well within the DSS 1σ of 20 meters. The TT&C and DSS range values used in GTDS are from ground to TDRS, whereas the BRTS range values are from ground to TDRS to BRTS.

In early 2000, FDF used a sequential filter to do orbit solutions for TDRS-3 simultaneously with all operational TDRSs and four user satellites: the Compton Gamma Ray Observatory (GRO), the Upper Atmospheric Research Satellite (UARS), the Hubble Space Telescope (HST), and the Extreme Ultraviolet Explorer (EUVE) (Reference 12). This sequential filter system has had evaluation and implementation by FDF for operational use and provides another source for estimating the range biases. With the filter, the TDRS-3 BRTS average residuals were approximately 1 meter, and the TT&C average residuals were approximately −11 meters.

By comparing the GTDS simultaneous solutions of other TDRSs with operational results, and the TDRS-3 simultaneous solutions with the filter results, it is believed that the routine TDRS-3 absolute 3σ errors with GTDS are now less than 50 meters.

3. MOMENTUM UNLOAD MODELING METHODS AND RESULTS

Plane constraints are listed, followed by delta-V optimization for momentum unloads, choice of solution epoch, calibration of delta-V with RWSP, and the frequency of solutions. Then pitch unload modeling results are presented, followed by calibrating delta-V from roll/yaw optimization and all solution results.

Plane Constraints

The same covariance constraints were used for the TDRS-3 study sample as were used for the other TDRSs (See Table 2). Just after the study period, a secular cross-track error was observed for TDRS-5 and -6, so the operational constrained plane covariances were increased on February 10, 2000, by a factor of four to 4×10^{-12} degree^2. For 3 weeks, these looser constraints were used operationally, until a large cross-track error was seen again for TDRS-6, possibly from solar sailing or effects of frequent roll/yaw unloads. During the same time, no growth in the TDRS-5 cross-track error was seen. Results similar to TDRS-5's were expected for other TDRSs. Since March 14, 2000, automated switching is done using either the original 10^{-12}-degree^2 constraints or no constraints, if no delta-V is in the solution arc. This retains the improvements from constraining the plane when an unload is modeled and determines the plane afresh when there are no unloads.

Modeling of Momentum Unloads

GTDS does not directly estimate delta-V in TDRS orbit solutions. Consequently, momentum unloads are modeled by applying an impulsive along-track delta-V, which is the major change to the orbit. WSC does not provide delta-Vs; instead, it provides the unload times and RWSP changes. Therefore, the relationship between delta-V and RWSP change must be empirically determined before GTDS can model roll/yaw unloads.

Delta-V Optimization for Roll/Yaw Unloads

The empirical relationships were determined using the optimization process described in Reference 2. Starting with zero, delta-V was adjusted to reduce the growth of the along-track difference of the predicted and the definitive ephemerides. The process was repeated until the 2.5-day along-track error changed less than 1 meter from the prior iteration or no further improvement could be obtained. The delta-V that met this criterion is called an "optimal delta-V".

Choice of Solution Epoch

In the prior roll/yaw analysis for other TDRSs, obtaining an optimal delta-V was difficult when the unload was before the orbital solution epoch and the predicted compare span, from which the delta-V was computed, was after the epoch. In early 2000, it was found that moving the solution epoch an hour (several integration steps) before the unload can improve the delta-V optimization. Epochs within 6 hours (1/4 orbit) of an unload yield similar results. A moved solution epoch may also significantly change solution parameters, especially the solar reflectivity coefficient (C_R) or possibly the range bias, and improve prediction accuracy for 1.5 days. Because the same C_R was used for the full propagation span, its disturbance for a solution containing momentum unloads significantly alters the propagation over the full span. The magnitude of the change for TDRS-1 through -7 is near 5 meters per day for a change in C_R of 0.01. Placing the epoch before the unload can aid in optimizing delta-V and in improving prediction errors over 1.5 days, even when no other change is done. Because this change in epoch sometimes improves and rarely degrades forward predictions for 1.5 days, this new procedure has been implemented when bias or C_R tolerance failures occur operationally. Bias tolerances are usually within 4 meters of the input range bias for TT&C and within 8 meters of the input range bias for BRTS. C_R tolerance limits are 1.35 and 1.47. Applying an average bias usually improves predictions when bias or C_R tolerance failures persist with an adjusted solution epoch.

Calibration of Delta-V with RWSP

After optimization, the RWSP change and the corresponding optimal delta-V value were plotted. When the actual RWSP change was not available, the predicted RWSP was used. Separate relationships were determined for positive RWSP changes and negative RWSP changes because different thruster pairs were used. Linear relationships were determined, as was done in the roll/yaw study for the other TDRSs (See Reference 2).

After the relationships between the RWSP change and delta-V were determined, these relationships were tested. First, the linear equation was used to compute a calibrated delta-V from a RWSP change. In the calibration phase, when a predicted RWSP change was not available, an actual RWSP was used. Next, this delta-V was used to model the momentum unload in the solution and ephemeris. Finally, the resulting ephemeris was compared to the definitive ephemeris. This comparison evaluated the predicted accuracy of the calibrated delta-V. Sometimes the predicted value was used instead of the actual, and sometimes only an actual value was available when a predicted value would have been used.

Daily versus Monday-Wednesday-Friday Solutions

Currently, orbit solutions for operational TDRSs are performed daily. This study assessed performances for both a daily and a Monday-Wednesday-Friday (M-W-F) solution update schedule. The current study contains predicted accuracies after 1.5 days and after 2.5 days. Accuracy of ephemerides generated on a daily schedule is indicated by the 1.5-day predicted accuracy measurements.

Accuracy of ephemerides generated on an M-W-F schedule is more complex to assess. On this schedule, there are three instances per week when predicted accuracy was assessed after 1.5 days of prediction and three instances when predicted accuracy was assessed after 2.5 days. The Sunday 3.5-day predicted span was omitted. In other words, each week had the same numbers of 1.5-day predictions as of 2.5-day predictions. Therefore, the accuracy of ephemerides generated on an M-W-F schedule was estimated by simply combining the accuracies of the two groups.

Pitch Unload Modeling Results

Reference 4 contains the standard modeling for TDRS pitch unloads, which is a linear relation of RWSP change and delta-V. Because of the good performance of this theoretical model, no adjustments are made operationally.

There were two cases of pitch unloads that were not close in time to any other momentum unloads during the prime period of this study before June 1999. Four other pitch unloads were used after November 1999. All six cases had comparisons below 35 meters over 1.5 days and below 38 meters over 2.5 days. The average comparisons without momentum unloads were 22 and 25 meters over the same spans. Based on this good performance, no adjustment to the theoretical delta-Vs is done for TDRS-3 pitch unload modeling.

Calibrating Delta-V from Roll/Yaw Optimization Results

Figure 4 gives results from the optimization portion of this study. Only the subset of study cases that were used for the optimization is plotted. For each TDRS, linear equations and correlation coefficients (R^2) are shown separately for negative and positive RWSP changes. Slopes are in units of millimeters per second (mm/s) per revolutions per minute (rpm).

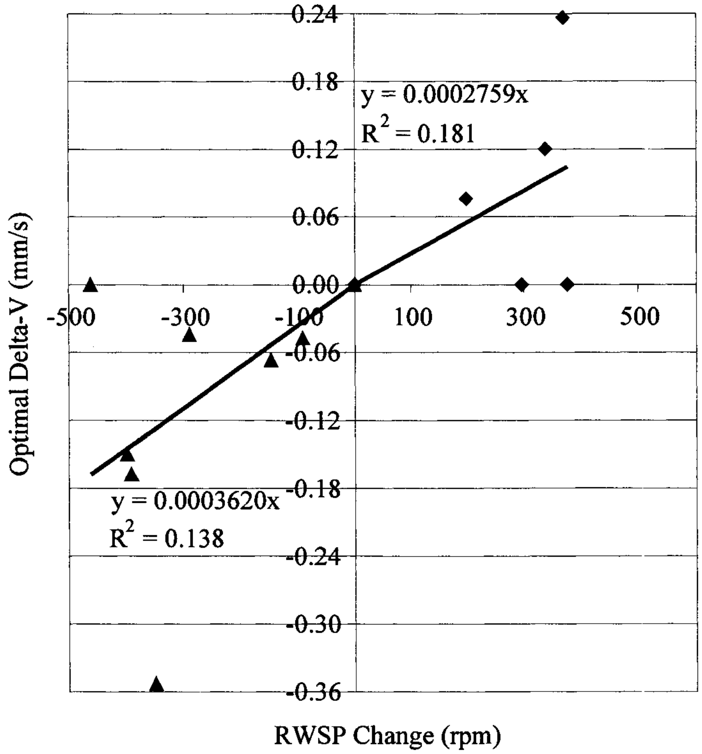

Figure 4. TDRS-3 Optimal Delta-V and Reaction Wheel Speed (RWSP) Change

For TDRS-3, the relationship between negative RWSP change and applied delta-V is modeled as a linear slope of 0.0003620 $mm \cdot s^{-1} \cdot rpm^{-1}$, with an R^2 correlation coefficient of 0.14. The relationship between positive RWSP change and applied delta-V is modeled as a linear slope of 0.0002759 $mm \cdot s^{-1} \cdot rpm^{-1}$, with an R^2 of 0.18. All points in the graph were used in calibrating the relationship. The mass used was 1762 kilograms. The ratio of operational mass to the former mass should be used to rescale the slopes, especially after a significant change in mass. This applies to roll/yaw unloads for all TDRSs. The pitch unload modeling inherently uses the current mass. The steeper TDRS-3 roll/yaw slope, 0.0003620, would induce a change of 47 meters over 1 day after the largest TDRS-3 roll/yaw unload (-489 rpm) in our sample.

In two cases in July 1998, solution noise was comparable to the effect of a roll/yaw unload. These two of the fourteen study cases were not used for optimization and are discussed below. All cases used in the optimization part of the study were also used in the calibration part.

For TDRS-3, most predicted RWSPs were not available in our sample. However, the three points with the optimal delta-Vs farthest from either line for both thruster pairs did have predicted RWSP. Using the predicted RWSP for these three points would change the slopes by less than 2 percent, but would improve the correlation coefficient R^2 by over 30 percent.

After further consideration, it is deemed better to do both optimization and calibration using only predicted RWSP changes. Then, if there is any bias in the predictions, as TDRS-4 roll/yaw unloads have, this calibration would automatically account for the bias. The TDRS-4 positive roll/yaw unload RWSP predicted changes are generally lower than the actual RWSP changes. Therefore, the calibration slope will be correspondingly steeper. If, on the other hand, the predictions have no bias, or only random noise in them, using the actual RWSP changes for optimizing and then the predicted RWSP changes for calibrating will be essentially the same as using predicted RWSP changes for both. So, using only the predicted RWSP changes in both optimization and in calibration can directly help improve the calibration results, as well as making the process simpler because the predicted RWSP changes are always used operationally.

In an attempt to improve the fit determined slopes, the timing of unloads was reviewed to search for any dependence of optimal delta-V on the time of day of the unload. None was found. It is conjectured that self-shadowing of a TDRS on its thrusters may affect momentum unload burn efficiency.

Two cases that were initially included in the study, –Z1A/–Z3A thruster pair momentum unloads on July 8 and 11, 1998, were later discarded. These two cases occurred during a brief time when the BRTS Multiple Access (MA) and Single Access (SA) range data varied by several meters, early after the Guam station began supporting TDRS-3, and are not included in the eighty-three cases in Table 7. Seven other optimization cases were done successfully for the –Z1A/–Z3A thruster pair.

The calibrations of delta-V with RWSP were used to redo the optimization cases to achieve results as would have been done operationally, given the slopes above.

All Solution Results

Table 7 shows solution statistics of the estimated C_R, TT&C and BRTS biases in meters, the weighted root-mean-square (WRMS) of solutions, definitive (def.) overlap comparisons, and comparisons over 1, 1.5, and 2.5 days of predictions (pred.) with definitive ephemerides. The maximum comparison over 1.5 days was 63 meters, which is less than the Terra requirement; the average comparison was 23 meters. At 2.5-days, for cases with less than 1.5 days notice for a pitch unload, the largest maximum comparisons were 200 and 110 meters. Otherwise, the maximum 2.5-day comparison was 104 meters. The average of all 2.5-day comparisons was 40 meters. The definitive overlap comparisons were very similar to the 1-day predictions. The highest definitive overlap comparison (76 meters) was propagating the December 24, 1999 epoch backward through two momentum unloads. The forward propagation consistency was 34 meters. Removing this one point drops the average definitive overlap difference just below the mean 1-day prediction difference. Five 2.5-day prediction differences exceeded 97 meters. Two of these were from short notice of unloads mentioned above, and four of the five were associated with a combination of a pitch unload and a roll/yaw unload within a 17-hour period.

Table 7. TDRS-3 Solution Statistics

	C_R	TT&C Bias (meters)	BRTS Bias (meters)	WRMS	Def. Overlap (meters)	1-day Pred. (meters)	1.5-day Pred. (meters)	2.5-day Pred. (meters)
Average	**1.3980**	**–37.20**	**–11.79**	**0.156**	**17.9**	**17.0**	**23.0**	**39.8**
SD	0.0245	13.92	14.64	0.059	12.9	12.1	13.2	33.6
Maximum	**1.4567**	**4.83**	**25.31**	**0.405**	**76.4**	**52.0**	**62.9**	**200.2**
Minimum	1.3129	–44.37	–28.40	0.062	3.2	3.0	5.1	4.4
Cases	83	83	83	83	74	69	65	52

2.5-Day Predictions

Out of fifty-two study cases, there were five cases for which either type of momentum unload modeling was not sufficient to meet the 75-meter predicted accuracy requirement after 2.5 days.

1.5-Day Predictions

Out of the sixty-one study cases, there were at least two cases for which pitch modeling alone was not sufficient to meet the 75-meter predicted accuracy requirement after 1.5 days. After the roll/yaw momentum unloads were modeled in daily solutions, all 1.5-day predictions were within 75 meters of definitive ephemerides.

Performance for both Monday-Wednesday-Friday and Daily Solutions

Table 8 gives performance results for solutions performed on an M-W-F schedule, which includes both the 1.5- and the 2.5-day results. Results show that when solutions are performed on an M-W-F schedule, 4.4 percent of the solutions fail the 75-meter accuracy requirement. This result would meet a 2σ 75-meter requirement.

Table 8. Performance for Solutions Three Times per Week

Prediction Span	Cases	Failures	Percent Failure	Sigma Requirement Met
2.5 Days	52	5	9.6 %	1σ
1.5 Days	61	0	0.0 %	3σ
1.5 and 2.5 Days	113	5	4.4 %	2σ

Table 9 gives performance results for solutions performed on a daily schedule, which includes only the 1.5-day results. Again, both pitch and roll/yaw unloads were modeled. Based on comparisons with definitive solutions, all daily solutions met the 75-meter 3σ accuracy requirement.

Table 9. Performance for Solutions Once per Day

Prediction Span	Cases	Failures	Percent Failure	Sigma Requirement Met
1.5 Days	61	0	0.0 %	3σ

4. SUMMARY AND RECOMMENDATIONS

This paper presents performance in meeting Terra requirements for TDRS-3 by modeling momentum unloads and estimating range biases. These 3σ requirements are 75 meters total positional accuracy and 5.5 millimeters per second total velocity accuracy predicted over 1 day onboard. Simultaneous orbit solutions were essential in estimating accurate range biases for TDRS-3. Modeling both pitch and roll/yaw momentum unloads is also required to meet the 75-meter requirement.

For a daily schedule, study results met the Terra requirement by at least 12 meters, compared with definitive ephemerides. Maintaining this performance operationally may require monthly assessment of range biases with simultaneous solutions, as well as closely monitoring for bias changes and for changes in roll/yaw momentum unloads.

To calibrate roll/yaw momentum unloads, we used actual reaction wheel speed (RWSP) changes for optimizing and predicted RWSP changes for calibrating, if both RWSP changes were available. Often only the actual values were available. For future analysis, it is recommended that the predictions be used for both optimizing and calibrating, so that if any bias exists in the predictions, this technique will be self-correcting. Moving the solution epoch before the unload aided at times both in optimization and in operational performance in modeling momentum unloads.

Study results did not always meet the Terra requirement when generating solutions on an M-W-F schedule. A major contributor to these failures was that there were often both pitch and roll/yaw unloads close together. Finer momentum unload modeling is required before the support may be done less often than daily. More precise simultaneous orbit determination may be achievable with the Ocean Topography Experiment (TOPEX)/Poseidon or Aqua (Earth Observing System PM-1) spacecraft and other TDRSs, perhaps with the user satellite as a constant in a TDRS-3 GTDS solution.

REFERENCES

1. National Aeronautics and Space Administration, Goddard Space Flight Center, *Earth Observing System AM-1 Detailed Mission Requirements*, November 1996
2. Computer Sciences Corporation, *TDRS Combined Pitch and Roll/Yaw Momentum Unload Modeling for Terra (EOS AM-1)*, memorandum from H. Offerman, D. Ward and L. Baxter, Code 453.2, to Mr. R. Caldwell, AlliedSignal Tech. Corporation, December 9, 1999
3. Computer Sciences Corporation, 6320-28221-320-01, *Improvement of BRTS Range Refraction Corrections for TDRS Orbit Accuracy*, M. Radomski, March 1998
4. Computer Sciences Corporation, *TDRS Pitch Momentum Unload Modeling for EOS AM-1*, memorandum from D. Ward and T. Thompson, Code 453.2, to Mr. R. Caldwell, AlliedSignal Tech. Corporation, December 23, 1998
5. J. Teles, M. Samii, and C. Doll, *Overview of TDRSS*, (paper presented at 30th COSPAR Scientific Assembly, Hamburg, Germany, July 11-21, 1994)
6. Computer Sciences Corporation, CSC-27434-40, *Summary of Tracking and Data Relay Satellite Orbit Determination and Prediction Accuracy Analyses*, W. Forcey et al., June 1997
7. Computer Sciences Corporation, 27434-43, *Orbital Determination Error Analysis for the Zone-of-Exclusion Tracking and Data Relay Satellite (TDRS-Z)*, D. Kelbel, T. Lee, M. MacWilliams, September 1997
8. White Sands Complex Spacecraft Engineering Group, *TDRS Momentum Unload Summary* (http://nmsp.gsfc.nasa.gov/WSC_SEG/momsumnow.htm), D. Perry, March 7, 2001
9. Computer Sciences Corporation, 27434-55, *Preliminary Assessment of the Accuracy of TDRS Orbit Determination Using Tracking from the K-Band Telemetry, Tracking, and Command System in Place of White Sands BRTS Tracking*, H. Offerman, D. Ward and W. Forcey, September 1997
10. D. Oza, D. Bolvin, J. Lorah, T. Lee, and C. Doll, *Accurate Orbit Determination Strategies for the Tracking and Data Relay Satellites*, (paper presented at the Flight Mechanics/Estimation Theory Symposium, Greenbelt, Maryland, May 16-18, 1995)
11. P. R. Bevington and D. K. Robinson, Data Reduction and Error Analysis for the Physical Sciences, 1969, First Edition, McGraw-Hill, Inc., New York, pp.58-59.
12. S. Wallace, *FDF COTS Infusion Operational Readiness Review*, [Consolidated Space Operations Contract (CSOC) presentation, Greenbelt, Maryland, March 30, 2000]